Atypical nighttime spread-F structure observed near the southern crest of the ionospheric equatorial ionization anomaly

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Abstract

An atypical nighttime spread-F structure is observed at or above the F-layer, near the crest of the ionospheric equatorial ionization anomaly region (EIA). This ionospheric atypical spread-F phenomenon was observed using two closed spaced (~115 km) ionospheric soundings stations located in Sao Jose dos Campos (23.21°S, 45.97°W) and Cachoeira Paulista (22.70°S, 45.01°W), Brazil, in a low-latitude station (near the southern crest of the EIA region), during nighttime, low solar activity, and quiet geomagnetic conditions. This structure, in the initial phase, appears as a faint spread-F trace above or at the F2-layer peak height. After a few minutes, it develops into a strong spread-F trace, and afterwards, it moves to altitudes below to the F2-layer peak heights.

Finally, the atypical nighttime F-layer trace structure may remain for a while between the F-layer bottom side and peak height or can move to an altitude above the F-layer peak height, and then it disappears. In order to have a comprehensive view of the ionospheric environment characterizing the phenomenon under study, complementary GPS data were used to investigate the ionosphere environment conditions, during both events. The 6 GPS stations used in this study are distributed from near the equatorial region to low latitudes.

1- Introduction

Several F-layer phenomena at equatorial and low-latitude regions have attracted considerable interest of different investigating groups for over fifty years. Among these phenomena, spread-F, zonal electric field pre-reversal enhancement (PRE), equatorial ionospheric anomaly (EIA), and F3-layer formation have been studied by numerous researchers. Nevertheless, these topics are still attracting much attention, particularly studies related to the day-to-day variability of these phenomena. In this paper, we report the occurrence of an atypical nighttime structure at or above the F2-layer, near the southern crest of the EIA (low latitude).

The ionospheric vertical electron density profile can be modified continuously by waves, chemistry, solar radiation, and solar activity. However, the main vertical features of the D, E, F1, and F2 layers are usually identifiable, except during strong geomagnetic storms. During daytime, the various ionospheric layers are normally present. During nighttime the D and F1 layers disappear, while the E layer takes some time to disappear, and, finally, only the F2-layer remains. Both theoretical and observational investigations, related to the day-to-day variability of the F-layer in equatorial and low-latitude regions, have become very active research subjects (Fagundes et al., 1999, 2009a, 2009b; Paul and DasGupta 2010; Tsunoda, 2010). The equatorial spread-F (ESF) phenomenon is one of the most studied topics. The onset conditions and the possible causes for the day-to-day ESF variability are hot topics in this research area (Abdu et al., 1982 and Sastri et al., 1997). Therefore, the knowledge related to ESF latitudinal and longitudinal morphology, seasonal and solar cycle variations for each longitudinal sector (American, Asian, and Indian), and zonal drift speeds has increased considerably during the last decade (Abalde et al., 2001; Bittencourt et al., 1997; Fagundes et al., 1995; Pimenta et al., 2001, 2003; Sahai et al., 2004, 2009, Sobral et al., 1999, 2011). Calvert and Cohen (1961) investigated some characteristics of spread echoes, at equatorial region, on ionograms and conclude that its main feature depend on (a) nature of the scattering irregularities and (b) the distribution of them in the east-west plane with respect to the ionosonde. In fact, by taking into account appropriate distribution of scattering centers in the east-west plane, they succeeded in simulating several features of the observed ESF signatures.

F3-layer formation and its day-to-day variability at equatorial and low latitudes is another topic that has become very active in the last decades. The F3-layer is characterized by the formation of an additional electron density peak above the F2-layer peak. Seasonal and solar cycle variations, their possible sources, and occurrence during geomagnetically quiet and disturbed periods are the primary subjects explored related to the F3-layer (Abdu et al., 1992, Balan and Bailey, 1995; Balan et al., 1997, 1998, 2008; Batista et al., 2002, 2003; Depuev and Pulinets, 2001; Jenkins et al., 1997; Lynn et al., 2000; Pulinets et al., 2002; Uemoto et al., 2006; Fagundes et al., 2007, 2011; Paznukhov et al., 2007; Rama Rao et al., 2005, Zain et al., 2008; Sreeja et al., 2009, 2010, Zhao et al., 2009, Klimenko et al., 2011). Near the equatorial region, F3-layer formation can be explained by the combined effects of a large **E x B** drift, during the morning period, which uplifts the F2-layer around the magnetic equator, and a meridional wind flowing from the summer hemisphere to the winter hemisphere, which acts to raise the plasma in the summer hemisphere. However, the meridional wind near the magnetic equator has a smaller vertical component than at a few degrees of latitude away from the magnetic equator, and, consequently, the F3-layer is weaker at the magnetic equator and stronger a few degrees away from it (Jenkins et al., 1997). Nevertheless, this mechanism based on the combined effects of **E x B** drift and meridional wind, proposed by Balan et al.(1997, 1998) for the equatorial region, does not explain F3-layer formation near the southern crest of the equatorial ionospheric anomaly (EIA) in the American sector (Fagundes et al., 2007 and 2011). Therefore, based on observations, Fagundes et al. (2007) proposed that medium scale traveling ionospheric disturbances (MSTIDs), generated by gravity waves (GWs), can play an important role in F3/F2-layer stratification in the regions near the EIA crests.

In this paper, we present and discuss two nighttime atypical spread-F events similar to those observed by Calvert and Cohen (1961) at equatorial region, but the present observations were carried out in Sao Jose dos Campos (23.21°S, 45.97°W) and in Cachoeira Paulista (22.70°S, 45.01°W), Brazil, in a low-latitude station (near the southern crest of the ionospheric equatorial ionization anomaly - EIA). The most interesting feature of this atypical F-layer structure is their time evolution. In the initial phase it appears as a weak spread-F at or above the F-layer trace peak height. Afterwards, the spread-F trace structure strengthens and moves to heights below the F-layer trace peak heights. Finally, this atypical structure shows electron density values larger than those of the F-layer and then disappears. Also, GPS data of six stations were used to investigate the ionospheric environment along the meridional direction from near equatorial region to low latitude and over the two ionosonde stations. Figure 1 shows a map indicating the geographical position of the ionosondes and GPS stations used in this work.

2- Observations and Results

Spread-F at equatorial and low-latitudes regions is a well-known phenomenon and is closely related to large-scale equatorial spread-F or plasma bubbles, associated with range spread-F signatures on the ionograms (Fagundes et al., 1999, Abalde et al., 2001). Also, in the equatorial and low-latitudes regions a second class of spread-F is observed, called frequency spread-F. Nevertheless, the observed spread-F phenomenon described in this investigation seems to be unrelated to large-scale equatorial irregularities. This ionospheric atypical spread-F phenomenon was observed from ionospheric soundings carried out in Sao Jose dos Campos (23.21^{o}S, 45.97^{o}W; hereafter referred to as SJC) and Cachoeira Paulista (22.70^{o}S, 45.01^{o}W; hereafter referred to as CP), Brazil, in a low-latitude station, two closed-spaced low-latitude stations (~115 km), near the southern crest of the EIA region, during nighttime, in geomagnetically quiet conditions, and low solar activity (Figures 2, 3, 4 and 5). These two closed spaced ionospheric stations (SJC and CP) are separated by ~0.5^{o} (57 km) in latitude and ~1^{o} (99 km) in longitude. Therefore, ionograms recorded almost simultaneously in these two stations, must have very similar traces. However, if small-scale irregularities propagate at ionospheric heights, in this region, then the ionogram traces observed in both sites will show differences. On the other hand, if large-scale ionospheric irregularities, with dimension of hundred kilometers, propagate over this region, it will be very difficult to notice any significant difference in the ionogram traces, in both sites. Therefore, these two closed spaced ionosonde stations have a good configuration to study small-scale structures propagating around these sites.

The six GPS data used in this work were obtained using the following receiving stations: Palmas (PAL), Brasilia (BRA), Rio Paranaiba (RPA), Rio de Janeiro (RIO), Ourinhos (OUR) and, Sao Jose dos Campos (SJC). These GPS stations are located from near the magnetic equatorial to the crest of the EIA region and over SJC and CP ionosonde stations. Figure 1 and Table 1 provide full details of the GPS receivers and the ionosonde stations considered in the present work. The GPS observations were used to obtain the rate of change of TEC, called ROT, this parameter is very useful to identify the presence of ionospheric irregularities (Aarons et al. 1997). The presence or absence of large-scale irregularities, around a specific station, show very clear signature in the ROT signals (see Figure 6). On the contrary, the presence of small-scale irregularities is more difficult to be observed by means of change of TEC (ROT parameter).

Figures 2, 3, 4, and 5 show step by step the development of the events observed on March 13, 2010 and March 19, 2010, in SJC and CP. Initially, the F2-layer presents its usual behavior after a weak post-sunset uplift, if this is compared with those characterizing days of "fresh spread-F" occurrence, probably associated with a small electric field pre-reversal enhancement (for more details about "fresh spread-F" see Fagundes et al., 2009a and 2009b). The ordinary and extraordinary traces are clear on the ionograms and the foF2 critical frequency varies from 4 to 6 MHz. However, slightly above the F2-layer peak height trace, a small spread-F structure trace appears, with frequencies that are higher than the F2-layer critical frequency (foF2). In the initial stage, this structure is faint and, apparently, not related with the F2-layer trace. However, after a few minutes, the structure trace becomes stronger and shows spread-F characteristics. Then the structure trace moves to heights between the bottom side and the peak of the F2-layer trace and turns into an atypical F-layer structure trace.

The four phases characterizing the nighttime atypical spread-F trace structure time evolution, that took place on March 13, 2010, are presented in Figures 2 and 3, for SJC and CP, respectively. The observed atypical phenomenon is very dynamical and changes rapidly its characteristics in a time scale of a few minutes. Figure 2A shows an ionogram with the first stage of the nighttime atypical spread-F trace structure in SJC at 03:05 UT (00:05 LT). The first echoes of this structure span between 530 km and 610 km in virtual height and range from 5.9 to 7.7 MHz. At this stage, in SJC, it is not clear if these echoes belong to an atypical F-layer trace structure. The ionogram observed at 03:07 UT (00:07LT) in CP does not show any evidence of this atypical spread-F trace structure, despite of the fact that these two sites are separated only ~115 km (Figure 3A). However, the first stage of the atypical spread-F trace structure appeared in CP only at 03:15 UT (00:15 LT - Figure 3B), indicating that the early stage of the spread-F trace structure appears in CP only 10 minutes later than in SJC. On the other hand at 03:10 UT (00:10 LT) in SJC (Figure 2B), the nighttime atypical spread-F trace structure becomes stronger and appears very clearly in the ionogram, with many more echoes. At this stage, the spread-F trace structure is well-developed above or at the F2-layer peak height, with frequencies higher than foF2, and there is a gap between the F2 critical frequency (foF2) and the range-type spread-F trace structure minimum echo frequencies. Again, a few minutes later, the atypical spread-F trace structure becomes stronger in CP (Figure 3C, 03:22 UT (00:22 LT)), but this ionogram shows both, a spread-F structure and satellite traces. By then, the spread-F trace structure has already became a satellite trace of the F2-layer in SJC at 03:20 UT (00:20 LT - Figure 2C). The F2-layer trace does not show spread-F trace occurrence and, on the other hand, the satellite trace (related to the spread-F structure) changes from range to frequency spread-F and presents a larger critical frequency than the F2-layer. A similar ionogram is observed in CP at 03:37 UT (00:37 LT - Figure 3D). Finally, Figure 2D (SJC) shows an ionogram recorded at 03:40 UT (00:40 LT), where the satellite traces (related to spread-F trace structure) and the F2-layer trace are seen to be much closer to each other.

Figures 4 and 5 show four phases of another similar atypical spread-F trace structure observed in SJC and CP on March 19, 2010. In the beginning of this event, the ordinary and extraordinary F2-layer traces appear very clearly on the ionograms, in SJC at 00:55 UT (21:55 LT). Again, the initial phase of the atypical structure trace initiates with a few spread-F echoes (Figure 4A), such as range spread-F trace, but these echoes appear above or at the F2-layer peak height trace and have frequencies between 5.0 to 5.5 MHz, which are higher than foF2 (3.4 MHz). In this initial stage, (00:55 UT - 21:55 LT) it is not clear whether these echoes belong to F-layer structure. It is important mote that also for this event the initial stage in CP appear 20 minutes later than in SJC, at 01:15 UT (22:15 LT) and remain until 01:22 (22:22 LT) (Figures 5A and 5B). A few minutes later in SJC (01:05 UT - 22:05 LT) or in the second phase, ordinary and extraordinary of the F2-layer traces remain clear on the ionograms (Figure 4B), but the spread-F trace structure is well developed. Nevertheless, the spread-F trace structure is well separated from the F2-layer trace. The frequency gap between the F2-layer critical frequency (foF2) and the first echoes of the spread-F trace structure is also in this case significant. Figure 4C and 5C show the third phase of the event at 01:55 UT (22:55 LT) and 01:52 UT (22:52 LT) for SJC and CP, respectively. The ordinary and extraordinary traces of the F2-layer are still clear, and only the atypical structure present spread-F.

However, this atypical spread-F trace structure merges with the F2-layer, close to the F2 peak height. The last phase of the phenomenon under study is shown in Figures 4D and 5D, in which the atypical spread-F trace structure starts moving upward and appears much more separated from the F2-layer trace. Finally, the structure disappears and the F2-layer recovers its normal characteristics. A sequence of ionograms, as a movie, for SJC and CP can be seen in the supplementary material, showing the time evolution of both events described in this paper. The time resolutions of ionograms are 5 minutes and 8 minutes for SJC and CP, respectively.

The rate of change of TEC (ROT) plots shown in Figure 6 for Mach 13 and 19, 2010 indicate that equatorial irregularities were generated during these nights, but were confined to equator and regions close by, as seen by the rapid and large ROT variations, recorded in PAL and BRA between 00:00 UT (21:00 LT) and 04:00 UT (01:00 LT) by most of satellites, black rectangle in Figures 6A and 6B). The ROT recorded at RPA shows some evidence that the irregularities formed at equator reached latitudes between BRA and RPA on March 13, because, even though smaller, some satellites show ROT variation, green rectangle, in Figures GA and 6B. On the contrary, the ROT recorded in RIO for both days, does not show any signature of equatorial irregularities.

Nevertheless, the presence of small-scale structure was observed in ORI and SJC, on March 13 (Figure 6), at the same time for which the atypical spread-F structure under study was observed by ionosonde in SJC and CP. It is important to highlight that this structure must be small, because only the satellites 3 and 19 detect the structure in ORI and satellite 19 in SJC (red rectangle, Figures 6A and 6B).

On the other hand, the atypical structure that was observed on March 19 by the ionosondes was probably even much tinier, because the ROT recorded in ORI shows a very small and short change amplitude variation (red rectangle, Figure 6B). But, the ROT in RPA, RIO and, SJC did not show ROT variation.

3- Discussion and Conclusions

Calvert and Cohen (1961) by observing atypical ionograms in Huancayo, at the magnetic equator, noticed atypical spread-F trace signatures similar to those we illustrated in this paper. Unlike Calvert and Cohen (1961), the events described in this work were observed at low-latitudes, near the southern crest of the EIA. They mentioned that the observed irregularities were apparently anomalous and are more closely related to spread-F observed at mid-latitudes than the equatorial spread-F and used the ray traced technique and concluded that the anomalous traces on the ionograms were generated by irregularities away from the overhead ionosonde site. However, in their paper they do not discuss the possible generation sources for this kind of structure.

The atypical spread-F structure investigated in this paper at low-latitudes is not related to the large-scale irregularities coming from the equator. On the other hand, recently propagation of GWs and MSTIDs has been suggested as a possible source of F2-layer stratification and spread-F signatures at low-latitudes in the Brazilian sector. Abdu et al. (1982) proposed that stratification of the nighttime F2-layer, during the pre-sunrise period, over CP, is due to the passage of GWs. Pimenta et al. (2008), using a ground-based all-sky imaging system in CP, observed dark band structures (MSTIDs) propagating from southeast to northwest. These optical measurements showed that the MSTIDs move quasi-horizontally through the ionosphere and that they are frontal in nature. Amorim et al. (2011) evidenced the occurrence of spread-F at the same time that the all-sky images registered MSTIDs over the zenith of CP, and they found that both the peak height and the virtual height ionospheric parameters registered abrupt uplifting. Makela et al. (2010) observed interesting airglow OI 630 nm band structures extending from low-latitude to near-equatorial regions (type MSTID), propagating towards the northwest, during a deep low solar activity period. All these observations show that the presence of MSTIDs, at low latitudes, is a very common feature and can be a source irregularities causing spread-F signatures on the ionograms.

Both cases presented in this investigation are very interesting examples of an ionospheric structure developing at or above the F2-layer. The time evolution of the atypical nighttime spread-F structure reinforces the idea that ionization transport processes related to MSTIDs, propagating at low latitudes, may be a source for generating the F2-layer stratification or F3-layer (Abdu et al., 1982, Fagundes et al., 2007). However, the cases illustrated in this work suggest that MSTIDs, in the initial phase, must have a strong horizontal component, as compared to the vertical component, and propagate just above or at the F2-layer peak height. In this case, it seems that the MSTIDS were able to construct a situation that caused spread-F formation. However, the spread-F was generated above the F2-layer peak height, which is very different from the large-scale spread-F that is usually generated near the F-layer bottom side. Another aspect to be considered is that this phenomenon may be somewhat related to the deep low solar activity period that took place in 2010.

The occurrence of an atypical spread-F structure at low latitudes is reported. The occurrence of this atypical phenomenon can be subdivided into four stages: 1) A faint structure is seen as a few echoes above the F2-layer in ionograms; 2) The structure becomes stronger and evolves into spread-F characteristics; but it is still not connected with the F2-layer; 3) The structure merges with the F2-layer and becomes an atypical spread-F; and 4) The atypical spread-F disconnects from the F2-layer and disappears, or it merges with the F2-layer and disappears. It is important mention that the structure was observed simultaneously by GPS ROT variation despite the GPS technique is good for to observe larger structures and during moderate-high solar activity, when the total electron content (TEC) is larger.

In this paper, we presented what appears to be another ionogram signature of MSTIDs propagating above or at F2-layer peak that generates an extra ionospheric structure just above or at the F2-layer, during nighttime, at low latitudes. The observation characteristics of this atypical nighttime spread-F trace structure indicate that some unknown or not well-understood generation mechanisms may be involved at equatorial and low-latitude regions. Also, the structure, in both occasions, is observed first at SJC and after a few minutes at

CP, suggesting that the structure propagates towards northeast. But, to determine the structure direction and speed velocity it is needed at least three ionosonde closed spaced. The GPS ROT data suggests that this structure is located around the two closed spaced ionosonde stations. Therefore, coordinated observations from multi-sites and multi-instruments (optical and radio) are relevant and important to understand the features of this kind of structure.

4- References

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Table 1. Details of the digital ionosondes (DI) and GPS sites used in the present study.

Location (Symbol)	Instrument	Coordinates	Dip Latitude
Palmas (PAL)	GPS	10.2º S, 48.2º W	05.7º S
Brasília (BRA)	GPS	15.9º S, 47.9º W	11.7º S
Rio Paranaíba (RPA)	GPS	19.2º S, 46.1º W	15.8º S
Cachoeira Paulista (CP)	DI	22.7º S, 45.0º W	19.2º S
Rio de Janeiro (RIO)	GPS	22.8º S, 43.3º W	19.8º S
Ourinhos (ORI)	GPS	22.9º S, 49.9º W	16.7º S
S. J. dos Campos (SJC)	DI and GPS	23.2º S, 46.0º W	17.6º S

Figure 1. A map showing the locations of the digital ionosonde and GPS and stations used in the present study. Also, the geographic and magnetic equators are shown.

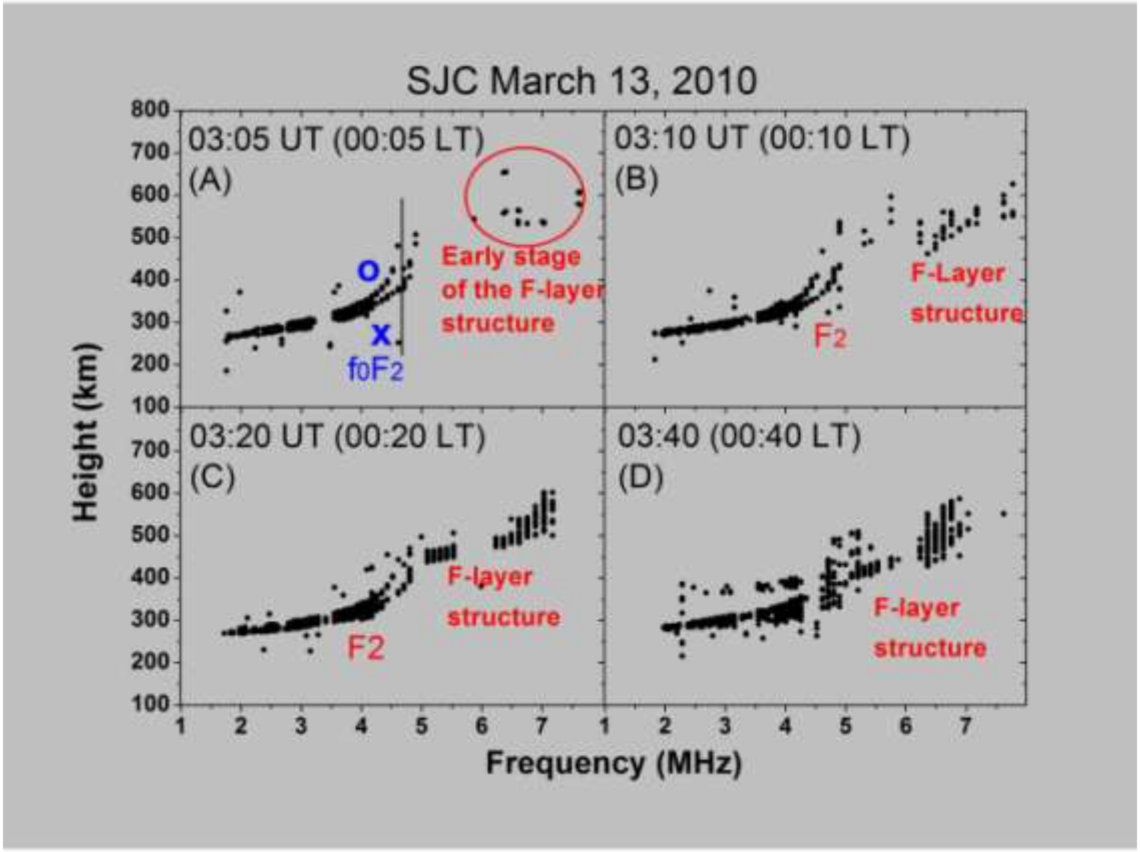


Figure 2. Ionograms obtained on March 13, 2010 for Sao Jose dos Campos A) The early stage of spread-F traces structure formation; "O" and "X" indicate the ordinary and extraordinary traces; critical frequency foF2=4.6 MHz. B) The spread-F traces structure became stronger. C) Spread-F traces structure became a satellite trace to the F2-layer traces. D) The satellite traces (spread-F traces structure) and the F2-layer traces are much closer.

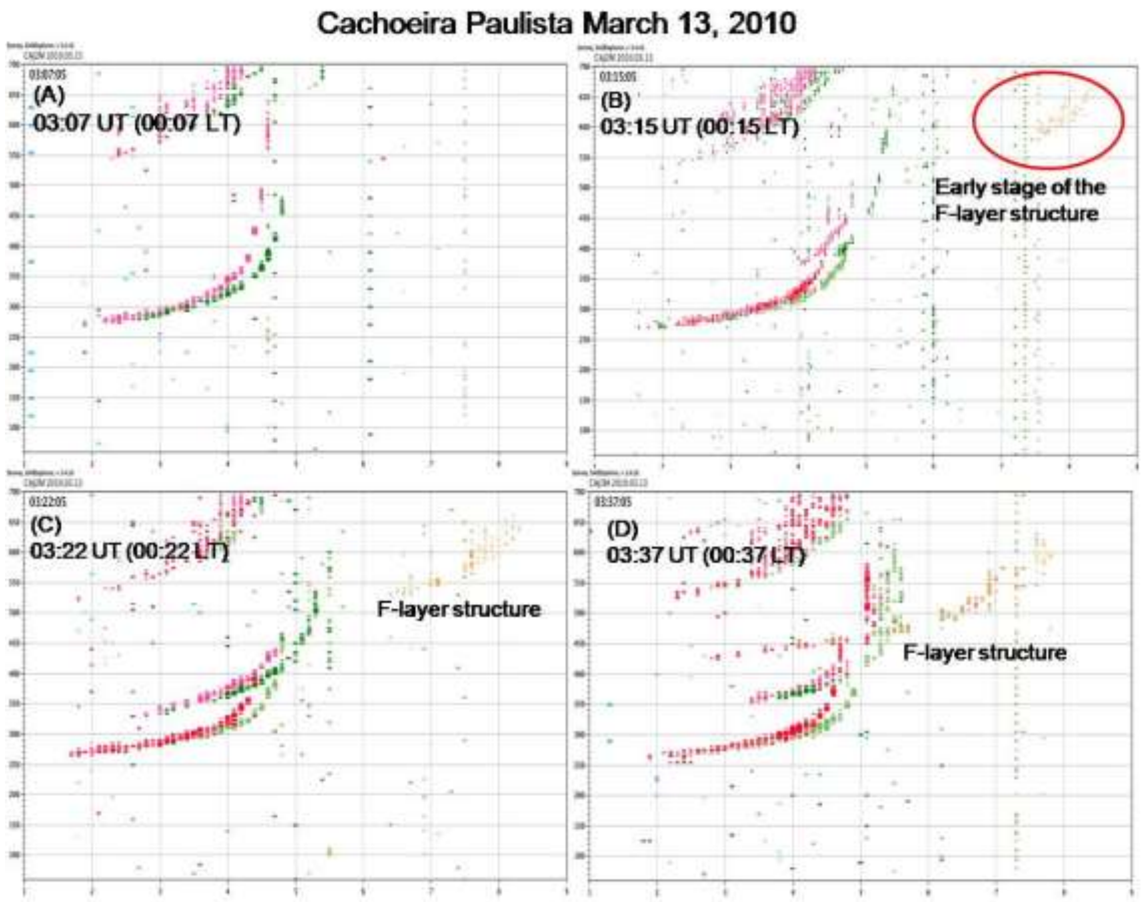


Figure 3. Ionograms obtained on March 13, 2010 for Cachoeira Paulista. A) Ionogram just before the spread-F traces structure appears. B) The early stage of spread-F traces structure formation. c) The spread-F traces structure becomes stronger. D) Spread-F traces structure became satellite traces of the F2-layer.

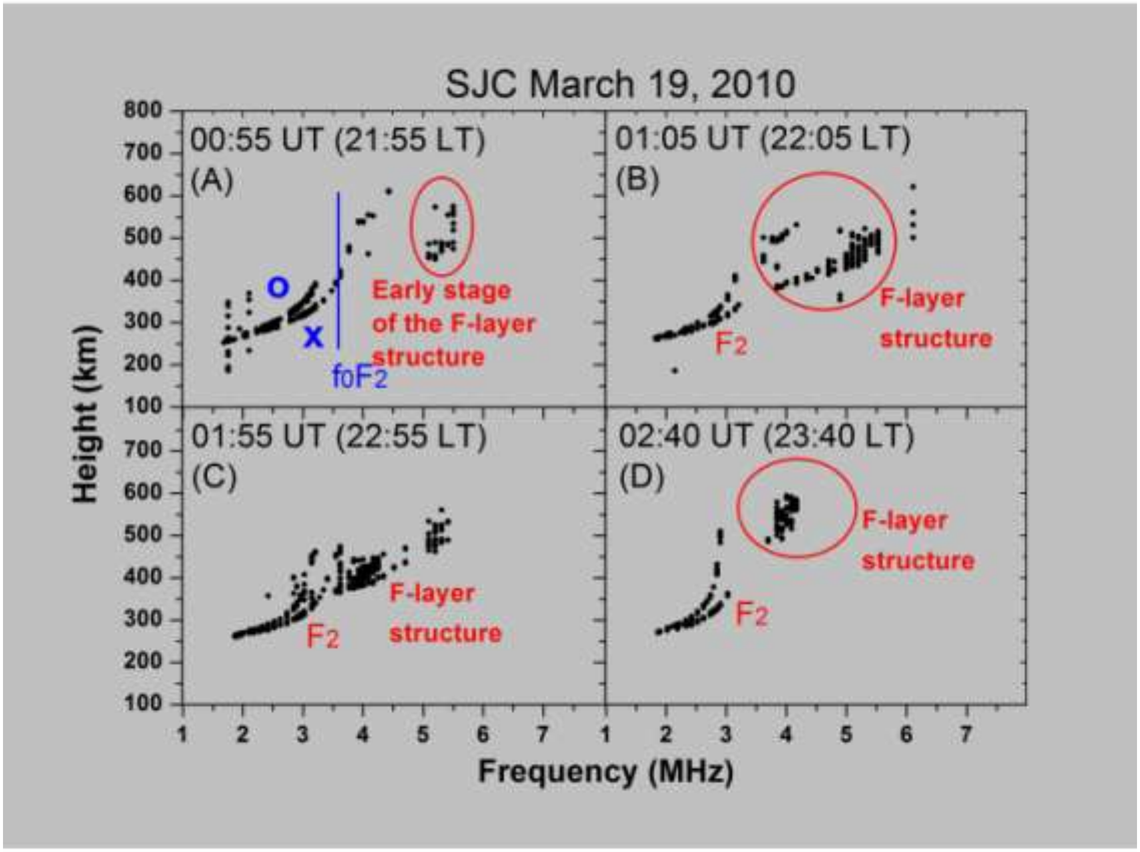


Figure 4. Ionograms obtained on March 19, 2010 for Sao Jose dos Campos A) The early stage of F3 spread-F formation; "O" and "X" indicate the ordinary and extraordinary traces; critical frequency foF2=3.5 MHz. B) The spread-F traces became stronger. C) The spread-F traces structure became satellite traces of the F2-layer traces. D) The spread-F traces get higher altitudes.

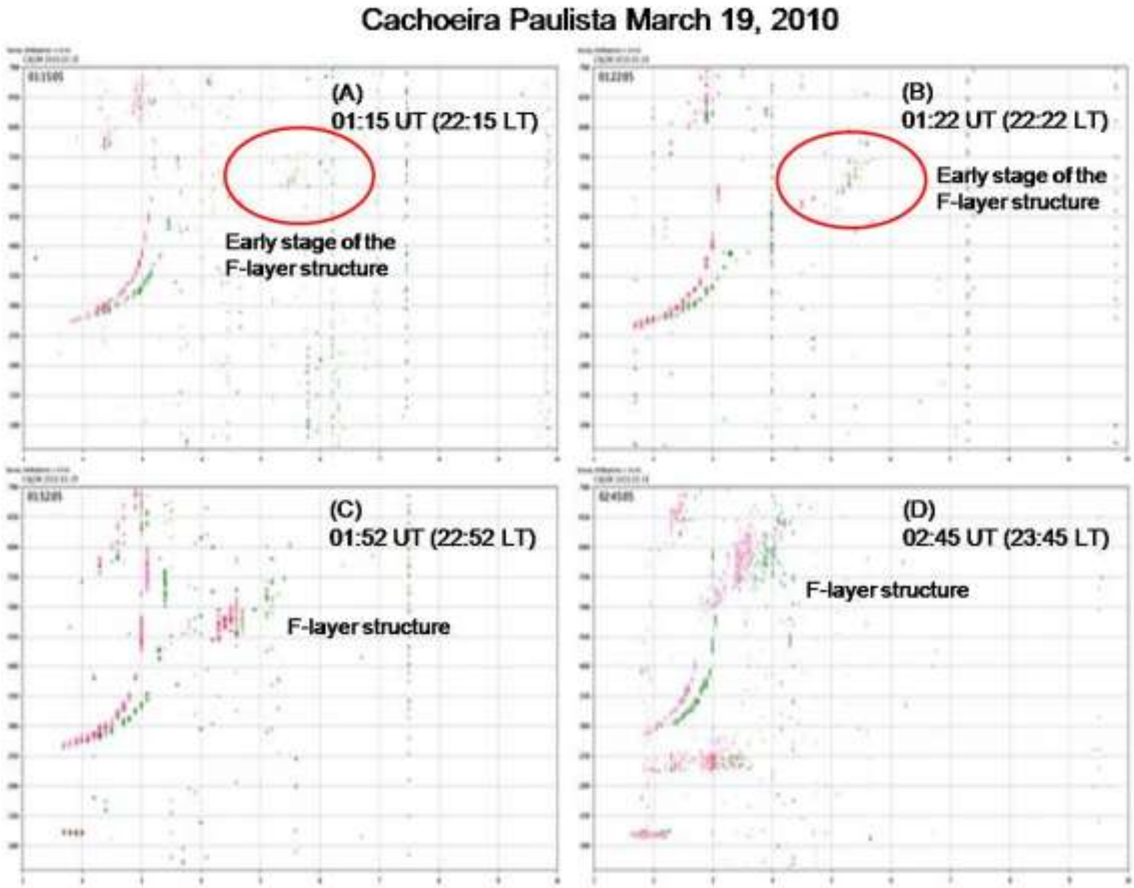
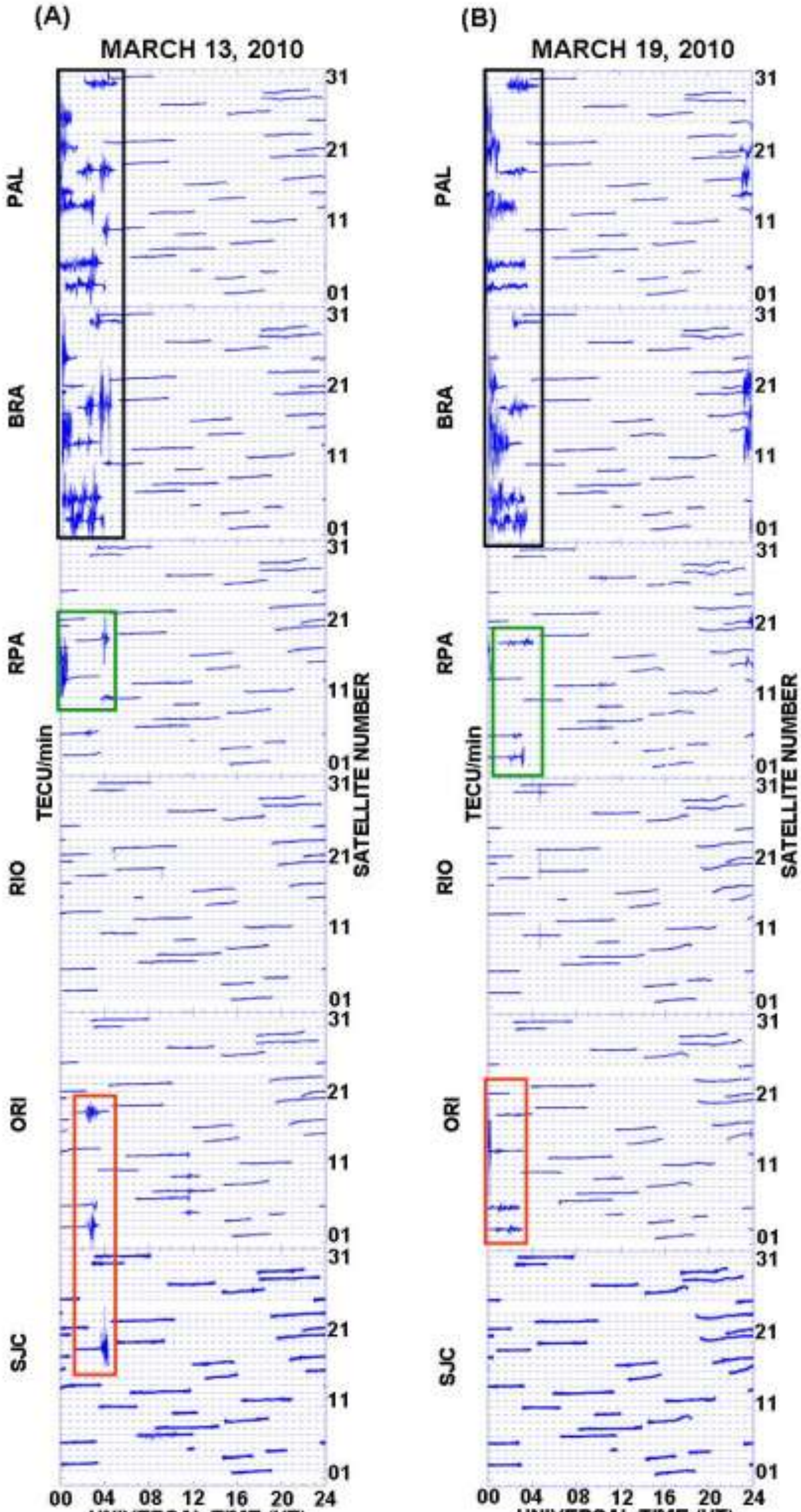


Figure 5. Ionograms obtained on March 19, 2010 for Cachoeira Paulista. A) The early stage of spread-F traces structure formation. B) The early stage of spread-F traces structure formation. C) The spread-F traces becames stronger. D) The spread-F traces structure get higher altitudes.


(A)
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(B)
MARCH 19, 2010
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Figure 6- The phase fluctuations (ROT - rate of change of TEC) from GPS observations obtained from different satellites at 6 receiving stations during the period March 13 and 19, 2010.